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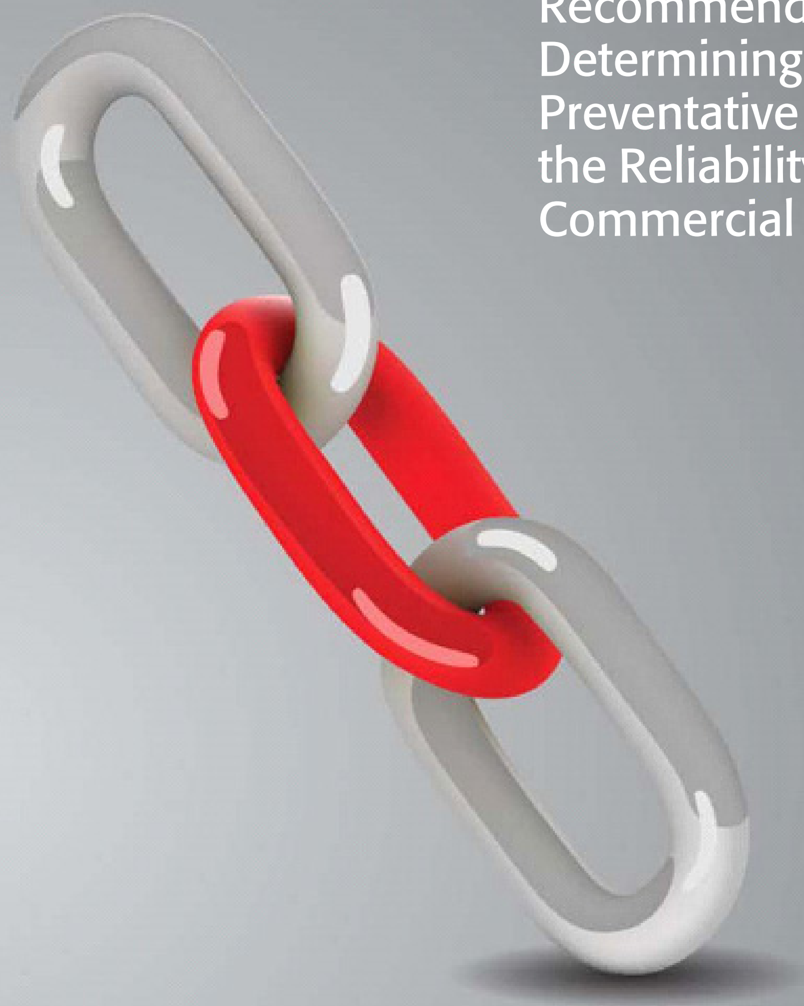
IEEE Std 3006.3™-2017

Recommended Practice for Determining the Impact of Preventative Maintenance on the Reliability of Industrial and Commercial Power Systems



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IEEE Recommended Practice for Determining the Impact of Preventative Maintenance on the Reliability of Industrial and Commercial Power Systems

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IEEE Industry Applications Society

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IEEE-SA Standards Board

Abstract: This recommended practice describes how to determine the impact of preventive maintenance on the reliability of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in the area of reliability. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: availability, failure mode, IEEE 3006.3™, mean time between failures, reliability

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Introduction

This introduction is not part of IEEE Std 3006.3-2017, IEEE Recommended Practice for Determining the Impact of Preventative Maintenance on the Reliability of Industrial and Commercial Power Systems.

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This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society, as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new book, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new book will cover the fundamentals of planning, design, analysis, construction, installation, start-up, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional "dot" standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

— Power Systems Design (3001 series)

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— Power Systems Grounding (3003 series)

— Protection and Coordination (3004 series)

— Emergency, Stand-By Power, and Energy Management Systems (3005 series)

— Power Systems Reliability (3006 series)

— Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a "dot" standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

The material in this recommended practice largely comes from Chapter 5 of IEEE Std 493™-2007 (*IEEE Gold Book*™).

IEEE Std 3006.3

The objective of this recommended practice is to illustrate the important role effective maintenance plays in the reliability and availability of power systems for industrial plants and commercial buildings. Details of "when," "how," and "how often" can be obtained from other sources.

Of the many factors involved in reliability and availability, preventive maintenance often receives meager emphasis in the design phase and operation of distribution systems when it can be a key factor in high reliability and availability. Large expenditures for systems are made to provide the desired reliability and availability; however, failure to provide timely, high-quality effective maintenance leads to system or component malfunction or failure and prevents obtaining the intended design goal.

Contents

IEEE Recommended Practice for Determining the Impact of Preventative Maintenance on the Reliability of Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice describes how to determine the impact of preventive maintenance on the reliability of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in the area of reliability. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 493™, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (*IEEE Gold Book*™).[1,2]

IEEE Std 3006.2™, Recommended Practice for Evaluating the Reliability of Existing Industrial and Commercial Power Systems.

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IEEE Std 3006.5™, IEEE Recommended Practice for Use of Probability Methods for Conducting Reliability Analysis of Industrial and Commercial Power Systems.

IEEE Std 3006.9™, IEEE Recommended Practice for Collecting Data for Use in Reliability, Availability, and Maintainability Assessments of Industrial and Commercial Power Systems.

IEEE Std 3007.2™, IEEE Recommended Practice for Maintenance of Industrial and Commercial Power Systems.

3. Definitions and acronyms

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[3]

availability: **(A)** (general) The ability of an item—under combined aspects of its reliability, maintainability, and maintenance support—to perform its required function at a stated instant of time or over a stated period of time. **(B)** (As a performance metric for individual components or a system) The long-term average fraction of time that a component or system is in service and satisfactorily performing its intended function. **(C)** (As a future prediction) The instantaneous probability that a component or system will be in operation at time *t*.

breakdown/corrective maintenance: Repair actions that are conducted after a failure in order to restore equipment or systems to an operational condition.

failure effect: A description of how the failure affects the device involved in the failure as well as other equipment in the system.

failure mode: Failure mode is defined as "the manner of failure". Failure mode is a description of how we can observe a fault. It is the way a piece of equipment fails, such as open or short circuited, or a description of what has failed to operate properly, such as loss of communication with a sensor.

failure modes and effects analysis (FMEA): The identification of significant failures, irrespective of cause, and their consequences. This term includes electrical and mechanical failures that could conceivably occur under specified conditions and their effect on system operation, adjoining circuitry, or mechanical interfaces.

failure modes, effects, and criticality analysis (FMECA): The identification of significant failures, their consequences, and their criticality. Analyzing failure criticality involves classifying or prioritizing the level of importance for each failure based on the failure rate and the severity of the effect of failure.

fault tree analysis (FTA): FTA is a systematic, deductive methodology for determining all of the credible ways for a specific undesirable event to occur. The undesirable event to be analyzed is the "Top Event" of the Fault Tree. The Fault Tree uses Boolean algebra (AND gates, OR gates, etc.) in a graphical representation to show the logical interrelationships between the initiating "basic events," such as component failures, and the top event.

hidden/latent failures: An abnormal or detrimental condition about which no one would know in the normal course of operation. An example is a device failure that does not occur immediately at the time of overstress, but sufficiently weakens the device so that it later fails under normal operating conditions.

[3] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org.

inherent availability (Ai): Long-term average fraction of time that a component or system is in service and satisfactorily performing its intended function. *Ai* considers only downtime for repair of failures. No logistics time, preventive maintenance, etc., is included.

mean time between failures (MTBF): The mean exposure time between consecutive failures of a component.

mean time to repair (MTTR or simply r): The mean time to replace or repair a failed component. Logistics time associated with the repair, such as parts acquisitions, crew mobilization, are not included. It can be estimated by dividing the summation of repair times by the number of repairs and, therefore, is practically the average repair time. The most common unit in reliability analyses is hours (h/f).

operational availability (Ao): long-term average fraction of time that a component or system is in service and satisfactorily performing its intended function. A_o differs from A_i in that it includes all downtime. Included are downtime for the repair of failures, scheduled maintenance, and any logistics time required (such as obtaining the necessary parts and scheduling the technician to perform the repair).

predictive maintenance: The practice of conducting diagnostic tests and inspections during normal equipment operations in order to detect incipient weaknesses or impending failures.

preventive maintenance: The practice of conducting routine inspections, tests, and servicing so that impending troubles can be detected and then reduced or eliminated.

probability density function (PDF): In statistics, the mathematical equation that relates the probability of a specific occurrence to time in operation. The probability density function most commonly used is the distribution function for the probability of failure versus time. The probability density function for a continuous random variable F is the derivative of cumulative distribution function (F(t)) with respect to t.

probability of failure: the unreliability of a component or system, the complement of reliability; probability of failure = (1 – reliability).

reliability: The probability that a component or system will perform required functions under stated conditions for a stated period of time.

3.2 Acronyms

Ai	inherent availability
Ao	operational availability
FMEA	failure modes and effects analysis
FMECA	failure modes, effects, and criticality analysis
MTBF	mean time between failures
MCCB	molded case circuit breaker
MOV	metal oxide varisor
MTTR	mean time to repair
PDF	probability density function
PM	preventive maintenance
RCM	reliability centered maintenance
SPD	surge protective device

4. Introduction

Many electrical engineers involved in the design, installation and maintenance of industrial and commercial power systems are much more familiar with the technology of power engineering than they are with reliability engineering (including some of the authors for this standard). If you are one of the first group and some of the definitions in this standard are not already familiar to you, particularly how a reliability engineer defines "reliability" and "availability," IEEE Std 3006.5-2014 provides an overview and explanations of reliability engineering as it is applied to power distribution systems.

The objective of this recommended practice is to illustrate the important role maintenance plays in the reliability and availability of power systems in industrial plants and commercial buildings. Details of "when," "how," and "how often" can be obtained from other sources (see Curdts [B2], Department of Army Maintenance Technical Manual [B3], "Factory Mutual Systems Transformer Bulletin" [B8], Hubert [B11], IEEE Committee Report [B18], "Maintenance Hints" [B19], NFPA 70B-2016 [B22], Miller [B20], Shaw [B26], Smeaton [B27], IEEE Std 1242 [B16]).

Of the many factors involved in reliability and availability, proper maintenance often receives meager emphasis in the design phase and operation of distribution systems when it can be a key factor in high availability. Large expenditures for systems are made to provide the desired reliability and availability; however, failure to provide timely, high-quality maintenance leads to system or component malfunction or failure and prevents obtaining the intended design goal.

Experience indicates that equipment lasts longer and performs better when covered under an effective maintenance program. An effective maintenance program can reduce accidents and operator error, and minimize costly breakdowns and unscheduled outages by identifying and solving problems early, before they become major problems.

It must also be clearly understood that a maintenance program can only preserve the quality and functionality of the existing design. Installation errors may be located and corrected as part of a maintenance program and thus improve the reliability and availability of the system as it was installed. However, perfect maintenance cannot raise the reliability and availability of the system above what is inherent to the design. If there are concerns about whether or not the existing design will meet the reliability and availability required for the system operation, IEEE Std 3006.2-2016 provides guidance.

4.1 Types of maintenance

IEEE Std 3007.2-2010 discusses three types of maintenance for electrical power equipment; breakdown/corrective maintenance, preventive maintenance and predictive maintenance. The first, breakdown/corrective maintenance is just fixing the equipment when it breaks. Nothing is done to keep the equipment from failing, or to extend the time it operates before it fails. For this standard, run to failure is considered "no maintenance" and both predictive and preventive maintenance are included when this standard discusses "preventive maintenance."

Reliability centered maintenance (RCM) is the process for determining the optimum mix of maintenance activities (corrective, predictive or preventive) to apply to the various parts of the electrical distribution system to maintain the needed reliability and availability at the minimum overall cost.

5. Relationship of maintenance practice and equipment failure

The Reliability Subcommittee of the IEEE Industrial and Commercial Power Systems Committee published the results of a survey that included the effect of maintenance quality on the reliability of electrical equipment in industrial plants (see IEEE Committee Report [B18]). Each participant in the survey was asked to give his or her opinion of the maintenance quality in the plant. A major portion of the electrical equipment covered

in the survey had a maintenance quality that was classed as "excellent" or "fair." Interestingly, maintenance quality had a significant effect on the percentage of all failures blamed on "inadequate maintenance."

As shown in Table 1, of the 1469 failures reported from all causes, inadequate maintenance was blamed for 240, or 16.4% of all the failures. It is also interesting to note that "Poor" maintenance produced a higher percentage of failures than "None." Contrary the normal expectation that doing maintenance always puts the equipment into a better condition, the real world is that sometimes the maintenance is done incorrectly or incompletely and leaves the equipment in a worse condition.

The IEEE data also showed that "months since maintenance" is an important parameter when analyzing failure data of electrical equipment. Table 2 shows data of failures caused by inadequate maintenance for circuit breakers, motors, open wire, transformers, and all equipment classes combines. The percent of failures blamed on inadequate maintenance shows a close correlation with "failure, months since maintained."

Table 1—Number of failures versus maintenance quality for all equipment classes combined

Maintenance quality	Number of failures		Percent of failures due to inadequate maintenance (%)
	All causes	Inadequate maintenance	
Excellent	311	36	11.6
Fair	853	154	18.1
Poor	67	22	32.8
None	238	28	11.8
Total	1469	240	16.3

Table 2—Percentage of failure caused from inadequate maintenance versus month since maintained

Failure (months since maintained)	All electrical equipment classes combined (%)	Circuit breakers (%)	Motors (%)	Open wire (%)	Trans-formers (%)
Less than 12 months ago	7.4	12.5[a]	8.8	0[a]	2.9[a]
12 to 24 months ago	11.2	19.2	8.8	22.2[a]	2.6[a]
More than 24 months ago	36.7	77.8	44.4	38.2	36.4
Total	16.4	20.8	15.8	30.6	11.1

[a]Small sample size; less than seven failures caused by inadequate failures

From the IEEE data obtained, it was possible to calculate "failure rate multipliers" for transformers, circuit breakers, and motors based upon "maintenance quality." These failure rate multipliers are shown in Table 3 and can be used to adjust the equipment failure rates. "Perfect" maintenance quality has zero failures caused by inadequate maintenance.

Table 3—Equipment failure rate multipliers versus maintenance quality

Maintenance quality	Transformers	Circuit breakers	Motors
Excellent	0.95	0.91	0.89
Fair	1.05	1.06	1.07

Table continues

Table 3—Equipment failure rate multipliers versus maintenance quality *(continued)*

Maintenance quality	Transformers	Circuit breakers	Motors
Poor	1.51	1.28	1.97
All	1.00	1.00	1.00
Perfect maintenance	0.89	0.79	0.84

It should also be noted that the references for the data above are dated. Unfortunately, new data for all of the categories listed above is not available. There are some newer references for circuit breakers [B25]. [B23], which the reader may find useful.

6. Equipment preventive maintenance

6.1 Equipment deterioration

New equipment begins to deteriorate with installation, though the rate of deterioration can vary quite dramatically depending upon the type of equipment, the environment it operates in and the extent it is loaded/used. This is normal and if unchecked, the deterioration can progress and cause equipment malfunction or failure. Harsh environmental conditions and system stresses such as overload, severe duty cycle, load increases, circuit alterations, and changing voltage conditions can accelerate the deterioration process. An effective preventive maintenance program can detect and mitigate these conditions. Equipment preventive maintenance procedures should be developed to accomplish four basic functions: to keep the equipment clean, dry, minimize friction with proper lubrication and minimize the effect of corrosion. Water, dust, high or low ambient temperature, high humidity, vibration, component quality, and countless other conditions can affect proper operation of equipment. Without an effective preventive maintenance program, the risk of a serious failure increases.

6.2 Causes of electrical failure

A common cause of electrical failure is dust and dirt accumulation and the presence of moisture. This can be in the form of lint, chemical dust, day-to-day accumulation of oil mist and dirt particles, etc. These deposits on the insulation, combined with oil and/or moisture, become conductors and are responsible for tracking and flashovers. Deposits of dirt can cause excessive heating and wear, and decrease apparatus life. Electrical apparatus should be operated in a dry atmosphere for best results, but this is often impossible; therefore, precautions should be established to minimize entrance of moisture. Moisture condensation in electrical apparatus can cause copper or aluminum oxidation and connection failure.

Another common cause of electrical failure is intrusion by animals, such as rats and snakes. Keeping the equipment sealed sufficiently to prevent animal intrusions is also an important issue.

Loose connections are another cause of electrical failures. Vibration, particularly in devices that switch frequently such as motor starters is a very common cause for loose connections. Electrical connections should be kept tight and dry. Creep or cold flow can cause joint failure. Mounting hardware and other bolted parts should be checked during routine electrical equipment servicing.

Friction can affect the freedom of movement of devices and can result in serious failure or difficulty. Dirt on moving parts can cause sluggishness and improper electrical equipment operations such as arcing and burning. Checking the mechanical operation of devices, verifying proper lubrication, and manually or electrically operating any device that seldom operates should be standard practice.

Another very significant cause for electrical failure is operating the equipment outside of the intended voltage, frequency, current, temperature, etc. limits. Since failure to maintain one of these basic factors, such as the

voltage within proper limits can impact the entire power distribution system, both the control system and the protective equipment must be given significant emphasis in determining what proper maintenance is.

6.3 Preventive maintenance program

Procedures and practices should be initiated to substantiate that electrical equipment is kept clean, dry, and with minimal friction and corrosion by visual inspection, exercising, and electrical testing. Electrical preventive maintenance should be accomplished on a regularly scheduled basis as determined by inspection experience and analysis of any failures that occur.

A preventive maintenance program certainly will not eliminate all failures, but an effective program will minimize their occurrence. Preventive maintenance programs should evolve over time as the experience of the facility personnel and maintenance groups grows with the specific applications and installations. Fundamental flaws that cause continual problems should be removed and a better system installed. Maintenance procedures that do not prove their worth over time should be reduced or eliminated and only the necessary maintenance should be performed. Keep in mind that whenever maintenance is performed, there is always the possibility of introducing failures due to improper maintenance.

6.4 Design for preventive maintenance

Preventive maintenance should be a prime consideration for any new equipment installation. Effective preventive maintenance begins with good design that includes a conscious effort toward maintainability. Quality of the equipment and the workmanship of the installation, along with the configuration of the distribution system for the application are fundamental prerequisites in attaining a satisfactory preventive maintenance program. Focusing only on installation cost without regard for performing efficient and economic maintenance creates system designs that can only be maintained during outages, which often means they will not be maintained. In many instances the additional cost of performing maintenance plus lost production from outages due to lack of maintenance more than offsets the savings in initial cost. A system that is not adequately engineered, designed, and constructed will not provide reliable service, regardless of how good or how much preventive maintenance is performed.

6.4.1 Quality and installation of equipment

One of the first requirements in establishing a satisfactory and effective preventive maintenance program is to have good quality equipment that is properly installed. Examples of this are as follows:

a) Large exterior bolted covers on switchgear or large motor terminal compartments are not conducive to routine electrical preventive maintenance inspections, cleaning, and testing. Hinged and gasketed doors with a three-point locking system would be much more satisfactory.

b) Space heater installation in switchgear or an electric motor is a vital necessity in high humidity areas; this reduces condensation on critical insulation components. The installation of ammeters in the heater circuit is an added tool for operating or maintenance personnel to monitor their operation.

c) Motor insulation temperatures can be monitored by use of resistance temperature detectors, which provide an alarm indication at a selected temperature (depending on the insulation class). Such monitoring indicates that the motor is dirty and/or air passages are plugged.

d) Standardization of installed equipment enables site personnel to maintain single manufacturers' equipment such as diesel generators, switchgear, or circuit breakers instead of several different vendors. This also reduces spare parts inventory, tools, test equipment, and personnel training. However, standardization may introduce opportunities for common cause failure (CCF). Care should be taken to avoid CCF. There are some applications, such as in nuclear power plants in which diversity of equipment type and manufacture are considered to lessen the probability of CCF.

6.4.2 Installation of alternate equipment

The distribution system configuration and features should be based on the criticality of the load the system will be powering. Where critical loads are being fed, the system should be designed such that maintenance work is permitted without load interruption or with only minimal loss of availability. Often, equipment preventive maintenance is not done, or is deferred, because load interruption is required to a critical load or to a portion of the distribution system. This may require the installation of alternate equipment and circuits to permit routine or emergency maintenance on one circuit while the other one supplies the critical load that cannot be shutdown. Examples are as follows:

a) Dual circuits to critical equipment
b) Double ended substations
c) Tie circuit breakers
d) Drawout circuit breakers
e) Auxiliary power sources
f) Redundant utility feeds
g) Redundant on-site generators
h) Automatic Transfer Switches with bypass-isolation
i) Maintenance bypass for Uninterruptible Power Supply (UPS) systems

Equipment that is improperly applied will not give reliable service regardless of how good or how much preventive maintenance is accomplished. The most reasonably accepted measure is to make a corrective modification.

6.4.3 Concurrent maintainability

Many critical facilities that require “7 x 24 operation” (7 d a week, 24 h each day) have been designed for “concurrent maintenance.” This means that the entire electrical distribution system for the critical loads has been designed so part of the system can be shut down periodically to perform maintenance on it while the facility is functioning and performing all of the required operations. This requires a specially designed system with sufficient redundancy built in and multiple paths for the power to reach the critical loads.

7. Reliability centered maintenance

Reliability centered maintenance (RCM) is a logical, structured framework for determining the optimum mix of maintenance activities needed to sustain the operational reliability of systems and equipment while ensuring their safe and economical operation and support. RCM focuses on identifying preventive maintenance actions, but these actions can become corrective actions by default. That is, when no preventive action is effective or beneficial for a given item, then that item is run to failure (assuming safety is not at issue). RCM is focused on improving readiness, availability, and mission continuity through effective and economical maintenance. RCM focuses on the reliability of the overall system in completing the intended mission, whereas typical preventive maintenance programs focus on the preservation of the individual pieces of equipment without regard to their importance to the mission.

7.1 RCM approach

Before RCM, many believed that everything had a “right” time for some form of preventive maintenance. This usually resulted in component replacement or system overhaul. Many maintenance and engineering personnel believed that replacing parts or performing a system overhaul would reduce the frequency of operational

failures. Despite this common belief, the reliability and available data told a different story. In some instances, preventive maintenance seemed to have no beneficial impacts, and in some cases, preventive maintenance results in more problems by providing opportunity for maintenance-induced failures and mistakes.[B21]

a) The airline industry in the US observed that preventive maintenance did not always reduce the probability of failure and that some items did not seem to benefit from preventive maintenance at all, they formed a task force with the Federal Aviation Administration (FAA) to study the subject of preventive maintenance. The results of the study confirmed that preventive maintenance was only effective for items with certain failure patterns. Also concluded was that preventive maintenance is required only when necessary to assure safe operation. Otherwise, the decision to do or not do preventive maintenance should be based on economics. [B24], [B7]

b) The RCM approach provides a logical way of determining if preventive maintenance is appropriate for a given component. If action is required, the next step is to select the appropriate type of preventive maintenance. The RCM approach is based on the following guidelines:

    1) The purpose of preventive maintenance is to maintain an item's full function(s). RCM attempts to maintain equipment function to keep the system operational, not just keeping components functioning. Specific redundancy may improve system reliability, but does increase capital and life-cycle costs.

    2) RCM emphasizes the total system end to end. RCM concentrates on maintaining total system and process function, not individual component function.

    3) RCM maintains safety and reliability as the basis for decisions. The component failure characteristics must be known in order to evaluate the value in performing preventive maintenance. RCM considers not only simple failure rates, but also attempts to include the conditional probability associated with equipment age (failure probability for a given operating age bracket).

    4) RCM is directed by safety first, then economics. Safety must be the primary concern of any maintenance program. When determined that safety is not a factor, then preventive maintenance is justified on economic grounds.

    5) RCM recognizes the reliability limitations inherent in the design. Preventive and corrective maintenance cannot improve the inherent reliability built into the component; it is predetermined by its design. Preventive maintenance only hopes to maintain the component reliability inherent in the design of the component life.

    6) RCM is a learning and evolving process. The difference between the perceived and actual design life and failure characteristics is addressed through age (or life) exploration.

c) The RCM concept is changing the way preventive maintenance is regarded. Wide acceptance exists that not all components benefit from preventive maintenance. Even when preventive maintenance would be effective, provided safety is not compromised it is often less expensive to allow an item to "run to failure" rather than to do preventive maintenance.

While RCM originated to maintain safety and reduce preventive maintenance costs for the airline industry, other industries have embraced RCM. RCM is used to develop preventive maintenance programs for utility, nuclear, processing, and manufacturing plants. It is recognized that RCM is becoming a favored method for evaluating and developing a comprehensive maintenance program, due to the merging of the idea to improve system reliability and availability blended with the fiscal economic responsibility.

7.2 Relationship of RCM to other disciplines

Much of the analysis needed for reliability provides inputs necessary for performing an RCM analysis. The fundamental requirement of the RCM approach is to understand the failure characteristics of an item. As used

herein, failure characteristics include the underlying probability density function (PDF), the consequences of failure, and whether or not the failure manifests itself and, if it does, how. Reliability is measured in different ways, depending on one's perspective: inherent reliability, operational reliability, mission (or functional) reliability, and basic (or logistics) reliability. RCM is related to operational reliability.

a) Inherent versus operational reliability: From a designer's perspective, reliability is measured by "counting" only those failures that are design related. When measured in this way, reliability is referred to as *inherent reliability*. From a user's or operator's perspective, all events that cause the system to stop performing its intended function are failure events. These events certainly include all design-related failures that affect the systems' function. Also included are maintenance- induced failures, no-defect found events, and other anomalies that may have been outside the designer's contractual responsibility or technical control. This type of reliability is called *operational reliability*.

b) Mission or functional reliability versus basic or logistics reliability: Any failure that causes the product to fail to perform its function or mission is counted in *mission reliability*. Redundancy improves mission reliability. Consider a case where one part of a product has two elements in parallel where only one is needed. (One is redundant.). If a failure of one element of the redundant part of the product fails, the other continues to function allowing the product to do its job. Only if both elements fail will a mission failure occur. In "basic" reliability, all failures are counted, whether or not a mission or functional failure has occurred. This measure of reliability reflects the total demand that will eventually be placed on maintenance and logistics.

One RCM precept is that safety must always be preserved. Given that the RCM concept came out of the airline industry, this emphasis on ensuring safety should come as no surprise. RCM specifically addresses safety and is intended to ensure that safety is never compromised. In the past several years, environmental concerns and issues involving regulatory bodies have been accorded an importance in the RCM approach for some items that is equal (or nearly so) to safety. Failures of an item that can cause damage to the environment, or that result in some Federal or state law being violated, can pose serious consequences for the operator of the item. So the RCM logic is often modified, as it is in this text, to specifically address environmental or other concerns.

System maintainability is essential to a successful RCM program. RCM is a method for prescribing preventive maintenance that is effective and economical. Whether or not a given preventive maintenance task is effective depends on the reliability characteristics of the item in question. Whether or not a task is economical depends on many factors, including how easily the preventive maintenance tasks can be performed. Ease of maintenance, corrective or preventive, is a function of how well the system has been designed to be maintainable. This aspect of design is called *maintainability*. Providing ease of access, placing items requiring preventive maintenance where they can be easily removed, providing means of inspection, designing to reduce the possibility of maintenance-induced failures, and other design criteria determine the maintainability of a system.

7.3 RCM implementation plan

The RCM process starts in the design phase and continues for the life of the system as shown in Figure 1; several major tasks are required to implement the RCM concept. Tasks include:

a) *Conduct supporting analyses*. RCM is a relatively information-intensive process. To provide the information needed to conduct the RCM analysis, several supporting analyses are either required, often as prerequisites to beginning the RCM analysis, or desirable. These supporting analyses include the failure modes and effects analysis (FMEA), fault tree analysis (FTA), functional analysis, and others.

b) *Conduct the RCM analysis*. The RCM analysis consists of using a logic tree to identify effective, economical, and, when safety is concerned, required preventive maintenance. (As will be seen, preventive maintenance is required when safety is involved; if no preventive maintenance is effective, then redesign is mandatory.)

Planning to implement an RCM approach to defining the preventive maintenance for a system or product must address each of the tasks noted in the preceding paragraph. The plan must address the supporting design phase analyses needed to conduct an RCM analysis. Based on the analysis, an initial maintenance plan, consisting of the identified preventive maintenance with all other maintenance being corrective, by default, is developed. This initial plan should be updated through life exploration during which initial analytical results concerning frequency of failure occurrence, effects of failure, costs of repair, etc., are modified based on actual operating and maintenance experience. Thus, the RCM process is iterative, with field experience being used to improve upon analytical projections.

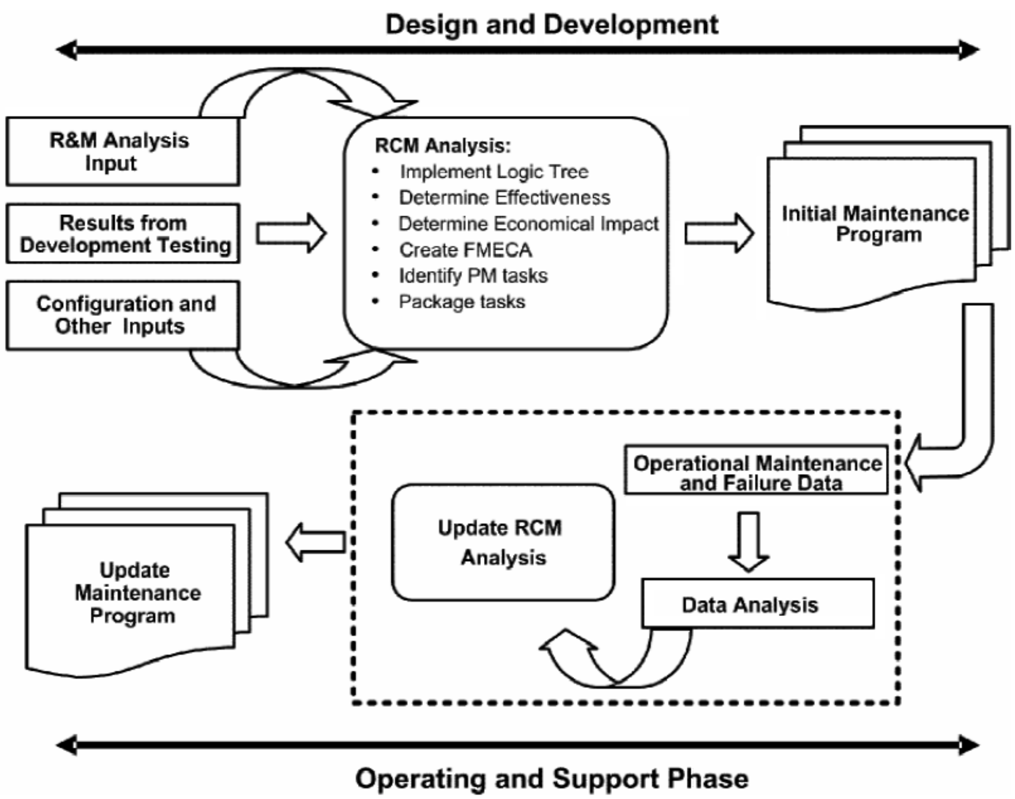

Figure 1—An overview of steps of the RCM process

7.4 Data collection requirements

7.4.1 Data categories

Since conducting an RCM analysis requires an extensive amount of information, and much of this information is not available early in the design phase, RCM analysis for a new product cannot be completed until just prior to production. The data falls into four categories: failure characteristics, failure effects, costs, and maintenance capabilities and procedures.

a) *Failure characteristics:* Studies conducted by the FAA and confirmed by later studies showed that preventive maintenance was effective only for certain underlying probability distributions. Components and items, for example, for which a constant failure rate applies (e.g., the underlying probability distribution is the exponential) do not benefit from preventive maintenance. Only when there is an increasing probability of failure should preventive maintenance be considered. Note that many components or systems are modeled with a constant failure rate, but in actuality many exhibit

wear-out characteristics, which require preventive maintenance. This is why RCM is performed on components by failure mode.

b) *Failure effects:* The effects of failure of some items are minor or even insignificant. The decision whether or not to use preventive maintenance for such items is based purely on costs. If it is less expensive to allow the item to fail (and then perform corrective maintenance) than to perform preventive maintenance, the item is allowed to fail. As stated earlier, allowing an item to fail is called run to failure.

c) *Costs:* The costs that must be considered are the costs of performing a preventive maintenance task(s) for a given item, the cost of performing corrective maintenance for that item, and the economic penalties, if any, when an operational failure occurs.

d) *Maintenance capabilities and procedures:* Before selecting certain maintenance tasks, the analyst needs to understand what the capabilities are, or are planned, for the system. In other words, what is or will be the available skill levels, what maintenance tools are available or are planned, and what are the diagnostics being designed into or for the system.

7.4.2 Sources of data

Table 4 lists some of the sources of data for the RCM analysis. The data elements from the FMEA that are applicable to RCM analysis are highlighted in item 2) of 7.1.1. Note that when RCM is being applied to a product already in use, historical maintenance and failure data will be inputs for the analysis. When historical data is not available or during the design phases of a system, generic data is an invaluable source for establishing a base line and making comparison analysis on the system.

Table 4—Data sources for the RCM analysis

Data source	Comment
Lubrication requirements	Determined by designer. For off-the-shelf items being integrated into the product, lubrication requirements and instructions may be available.
Repair manuals	For off-the-shelf items being integrated into the product.
Engineering drawings	For new and off-the-shelf items being integrated into the product.
Repair parts lists	For off-the-shelf items being integrated into the product.
Quality deficiency reports	For off-the-shelf items being integrated into the product.
Other technical documentation	For new and off-the-shelf items being integrated into the product.
Recorded observations	From test of new items and field use of off-the-shelf items being integrated into the product.
Hardware block diagrams	For new and off-the-shelf items being integrated into the product.
Bill of materials	For new and off-the-shelf items being integrated into the product.
Functional block diagrams	For new and off-the-shelf items being integrated into the product.
Existing maintenance plans	For off-the-shelf items being integrated into the product. Also may be useful if the new product is a small evolutionary improvement of a previous product.
Maintenance technical orders/manuals	For off-the-shelf items being integrated into the product.

Table continues

Table 4—Data sources for the RCM analysis *(continued)*

Data source	Comment
Discussions with maintenance personnel and field operators	For off-the-shelf items being integrated into the product. Also may be useful if the new product is a small evolutionary improvement of a previous product.
Results of FMEA, FTA, and other reliability analyses	For new and off-the-shelf items being integrated into the product. Results may not be readily available for the latter.
Results of maintenance task analysis	For new and off-the-shelf items being integrated into the product. Results may not be readily available for the latter.

7.5 Failure mode, effects, and criticality analysis

The failure mode, effects, and criticality analysis (FMECA) is a reliability evaluation and design technique that examines the potential failure modes for all of the components within a system in order to determine the effects of failure on the overall system and the equipment within the system. The FMECA is composed of two separate analyses: the FMEA and the criticality analysis (CA). The FMEA classifies each potential failure according to severity on the mission success and personnel/equipment safety. The CA will provide estimates of system critical failure rates based on past history and current information. [B7]

The FMECA should be initiated as soon as preliminary design information is available. The FMECA is a living document that is not only beneficial when used in the design phase but also during system use. As more information on the system is available, the analysis should be updated in order to provide the most benefit.

7.5.1 Example FMEA

To provide a better understanding of the RCM process, a portion of an RCM is provided here in which a FMEA is done for a 480 V main switchboard. (See Figure 1 and Figure 2.) Since the operating context for which the switchboard is providing power is not defined, this example covers only the part of the analysis that is common to all main switchboards.

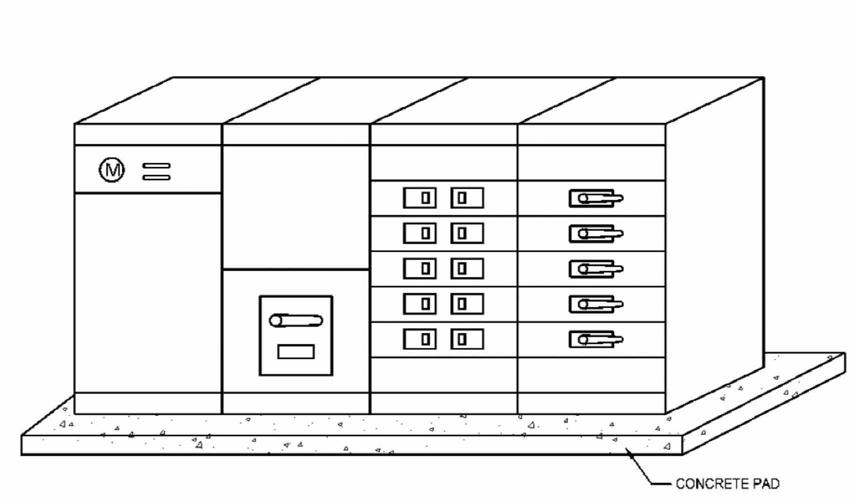

Figure 2—480 V main switchboard

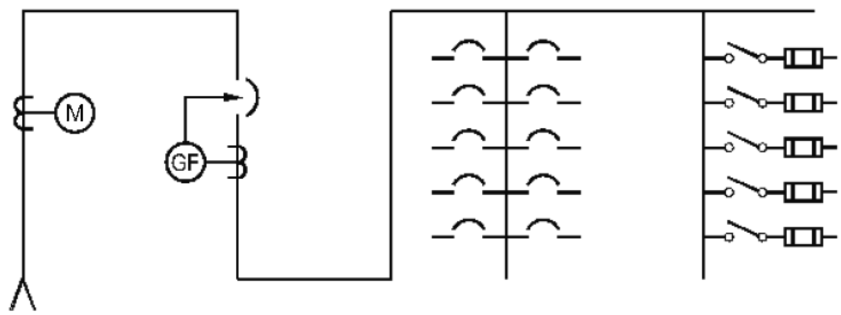

Figure 3—One-line drawing of 480 V main switchboard

For this example, the system consists of a 2000 A, 480 V main switchboard, without specifying the type of facility the switchboard serves. First, the aspects that are common to 480 V switchboards are discussed, and then how the type of facility the switchboard serves would influence what is optimum maintenance is discussed.

For the example system, the utility provides power with underground cables to a meter section in the switchboard. The switchboard has a 2000 A bolt-in, insulated-case, main circuit breaker. The circuit breaker is manually operated and has an electronic trip unit with long-time pickup and delay (for overload protection), instantaneous trip (for short-circuit protection), and ground-fault trip functions.

The switchboard has two distribution sections: one section with molded-case circuit breakers (MCCBs) that have thermal and magnetic trip elements and the other section with fused switches. The major components of the 480 V switchboard are as follows:

— Metal enclosure
— Circuit breakers
— Fused switches
— Control components and wiring
— Copper or aluminum bus bars, bolts, insulators, and barriers

The functions and failures of the 480 V main switchboard are detailed in Table 5:

Table 5—Functions and failure for the switchboard of Figure 3

Function	Failure
Provide electrical power to the facility	Interruption of power to one or all of the loads
Provide a means to turn the power on and off	Failure to turn the power on or off
Provide a means to lock the power off (lock-out and tag-out)	No means provided; the circuit can be closed when locked out
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard or downstream of it	Failure to detect an abnormality; failure to isolate an abnormality; failure to isolate an abnormality safely
Provide a barrier between the energized parts of the switchboard and the enclosure to prevent shock hazard	Failure to prevent a shock hazard

To evaluate the effect of the failures, several levels of effects need to be examined. “Local effects” in turn create “secondary effects” until an “end effect” is reached. As an example, for the local effect of a “failure to

isolate an electrical abnormality," a short circuit causes high current to flow through one of the circuit breakers in the distribution panel, but it does not trip. There are a couple of possible secondary effects: The main circuit breaker can trip, or the fault can burn itself clear. The end effect to the facility can be loss of power, but no damage (other than the equipment that has the short circuit) if the main circuit breaker trips by the ground fault function. However, if the fault has to burn itself clear and starts a fire while it is burning, then the end effect may be the destruction of the entire facility. This situation is also likely to create an increased arc-flash hazard; therefore, the maintenance of the circuit breakers, to minimize the risk of failure, is crucial to the safety of personnel working on or near the equipment.

From the above example, it is obvious that some effects are much more significant than others. Addressing the local effects of a failure in the 480 V switchboard, it becomes apparent that the failures are, in order of severity, fire and arc-flash safety hazard, loss of power to the facility, and loss of power to a single circuit. "Loss of power" will be discussed later in the analysis. This analysis starts with the "fire and arc-flash safety hazard."

WARNING

Electricity poses three threats to people: shock or electrocution from contact with live parts, burns from the arc-flash, and injury from the arc-blast of an electrical fault. The primary protection that the switchboard has to prevent injury to people is the metal covers around its outside. The covers have been designed to prevent contact with live parts. They also may provide some level of help in containing an arc-flash or arc-blast from a fault within the enclosure, particularly if the arc fault has low energy. However, only arc-resistant equipment has been designed to contain or safely divert the energy of an arc fault at the magnitude of the name plate rating. If the arc-flash or arc-blast from a fault is contained within the enclosure, it is also less likely to start a fire. In order for the covers to be effective, they must be securely latched, bolted, or screwed in place.

Therefore, it is obvious that the first and most significant hazard (shock or electrocution) can easily be avoided by keeping the covers on the switchboard and, when performing maintenance, **by turning the power off before the covers are removed**. See Table 6.

Table 6—FMEA for the switchboard of Figure 3

Functions	Failures	Component(s)	Local effect of failure	Cause of failure
Provide a barrier between the energized parts of the switchboard and the outside to prevent shock hazard and contain fault	Failure to prevent shock hazard	Metal covers	Fire or arc-flash safety hazard	Covers not installed
Provide a means to lock the power off (lock-out and tag-out)	No means provided	Mechanical device on the front of the breaker or fused switch	Safety hazard	No device provided
Provide a means to lock the power off (lock-out and tag-out)	Circuit can be closed when locked out	Mechanical device on the front of the breaker or fused switch	Safety hazard	Mechanical device on the front of the breaker or fused switch defective

The 480 V switchboard also provides overcurrent protection for electrical faults in the equipment it feeds by detecting overloads, short circuits, or ground faults and by automatically removing the electrical power. Since the example is a 2000 A, 480 V main switchboard, the main circuit breaker has ground-fault protection. The MCCBs and fuses have overload and short-circuit protection.

Following the above example for the fuses, Table 7 shows the functions, failures, component(s), local effect, and cause of the failure.

Table 7—FMEA for the switchboard—fused switch

Functions	Failures	Component(s)	Local effect of failure	Cause of failure
Provide a means to turn the power on	Failure to turn the power on	Fused switch mechanism	Fused switch will not close	Operator or mechanism failure
Provide a means to turn the power off	Failure to turn the power off	Fused switch mechanism	Fused switch will not open	Operator or mechanism failure
Provide a means to turn the power on	Failure to turn the power on	Fuse	Fuse open	Defective fuse or downstream fault caused the fuse to open
Provide power to the load	Interruption of power to load, no abnormality exists downstream	Fuse	Fuse open	Defective fuse or downstream fault caused the fuse to open

The same diagram gets more complex for circuit breakers since there are more components and circuit breakers have more failure modes.

In general, there are five major failure modes for a circuit breaker. It can:

a) Fail to open—mechanical failure of the operating mechanism or internal mechanism or in the case of a short circuit or overload, fail to detect the abnormal condition (fault); for electrically operated circuit breakers it can also be a failure in the opening coil or circuit providing the opening signal.

b) Fail to close—mechanical failure of the operating mechanism or internal mechanism; for electrically operated circuit breakers it can also be a failure in the closing coil or circuit providing the closing signal.

c) Open when it should not—mechanical failure of the internal mechanism or fault sensing mechanism; for electrically operated circuit breakers it can also be a failure in the circuit (falsely) providing the opening signal.

d) Close when it should not—mechanical failure of the internal mechanism; for electrically operated circuit breakers it can also be a failure in the circuit (falsely) providing the closing signal.

e) Fail to interrupt the fault—mechanical failure of the internal mechanism or the fault current exceeds the interrupting rating of the circuit breaker.

In the example above all of the circuit breakers and fused switches are manually operated, so none of the failure modes associated with electrically operated circuit breakers apply.

The failure modes for the main insulated case circuit breaker with an electronic trip unit are slightly different from the molded case circuit breakers. The electronic trip unit senses the abnormal condition from current transformer (or current sensor) mounted on the primary disconnect of the circuit breaker. Using the energy it receives from the current transformer for control power, it operates a device called a flux shifter to open the circuit breaker. The flux shifter is a magnetic spring-loaded device that only requires a small amount of power to release the magnet holding the spring and open the circuit breaker. Table 8 lists the failure modes and effects for the main circuit breaker with the electronic trip unit.

Table 8—FMEA for the switchboard—main circuit breaker

Functions	Failures	Component(s)	Local effect of failure	Cause of failure
Provide a means to turn the power on	Failure to turn the power on	Circuit breaker	Loss of production	Operator or mechanism failure
Provide a means to turn the power off	Failure to turn the power off	Circuit breaker	Fire or safety hazard	Operator or mechanism failure
Provide a means to lock the power off (lock-out and tag-out)	No means provided	Mechanical device on the front of the breaker	Safety hazard	No device provided
Provide a means to lock the power off (lock-out and tag-out)	Circuit can be closed when locked out	Mechanical device on the front of the breaker	Safety hazard	Mechanical device on the front of the breaker or fused switch defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect abnormality	Circuit breaker trip unit, current sensing, wiring	Damaged or destroyed electrical equipment	Circuit breaker trip unit defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect abnormality	Circuit breaker trip unit, current sensing, wiring	Damaged or destroyed electrical equipment	Circuit breaker current sensing defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect abnormality	Circuit breaker trip unit, current sensing, wiring	Damaged or destroyed electrical equipment	Circuit breaker wiring defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to isolate it	Flux-shifter or shunt trip mechanism, wiring, circuit breaker mechanism	Damaged or destroyed electrical equipment	Flux shifter or shunt trip mechanism defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to isolate it	Flux-shifter or shunt trip mechanism, wiring, circuit breaker mechanism	Damaged or destroyed electrical equipment	Circuit breaker mechanism defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to isolate it safely	Circuit breaker mechanism and arc chutes	Damaged or destroyed electrical equipment	Interrupting rating of circuit breaker is less than fault current available

The molded case circuit breakers have two internal elements to sense overloads and short circuits. The overload element is a bi-metallic strip. The two different metals have different thermal expansion coefficients, so the strip bends as it gets hot. The common failure mode for it is that the strip gets stuck in some manner and will not release the spring to open the circuit breaker. The short circuit element is an electro-magnet. A plunger is moved by the electro-magnet to release the spring and open the circuit breaker. The coil can open or the

plunger can fail to move or not move sufficiently to open the circuit breaker. The failure modes and effects for molded case circuit breakers are listed in Table 9.

Table 9—FMEA for the switchboard—molded case circuit breakers

Functions	Failures	Component(s)	Local effect of failure	Cause of failure
Provide a means to turn the power on	Failure to turn the power on	Circuit breaker	Loss of production	Operator or mechanism failure
Provide a means to turn the power off	Failure to turn the power off	Circuit breaker	Fire or safety hazard	Operator or mechanism failure
Provide a means to lock the power off (lock-out and tag-out)	No means provided	Mechanical device on the front of the breaker	Safety hazard	No device provided
Provide a means to lock the power off (lock-out and tag-out)	Circuit can be closed when locked out	Mechanical device on the front of the breaker	Safety hazard	Mechanical device on the front of the breaker or fused switch defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect overload	Bi-metallic strip	Damaged or destroyed electrical equipment	Bi-metallic strip defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect short circuit	Electro-magnet	Damaged or destroyed electrical equipment	Electro-magnet defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to isolate it safely	Circuit breaker mechanism and arc chutes	Damaged or destroyed electrical equipment	Interrupting rating of circuit breaker is less than fault current available

Next consider the secondary effects, a phrase that refers to what happens to the system the switchboard is feeding as a result of a local effect. For example, a circuit breaker can fail to open and isolate a fault. What does that event cause to happen? The circuit breaker directly upstream could trip, and the secondary effect is that a larger part of the distribution system is without power. If the protection system was poorly designed, installed, or maintained, the secondary effect could include a fire in addition to the tripping of the circuit breaker upstream.

In the switchboard example, the next step would be to consider the equipment supplied by the switchboard. In an actual RCM, the load being supplied is a critical element in the process. The goal of the RCM is to optimize the maintenance of the power system so the facility can perform its intended mission. If the intended mission is to power a manufacturing facility five days a week for one or two shifts a day, the optimum maintenance would most likely be much different from the optimum for a manufacturing facility that operates 24/7.

The RCM process includes looking at each failure mode and all of the effects that each mode could cause. The local effect (for example, a circuit breaker fails to close) causes a secondary effect (for example, the pump fails to run), which ultimately causes the end effect (for example, a manufacturing line fails to start or it shuts down).

Once all of the effects have been determined, the effects are normally broken down into a gradient scale such as the one shown in Figure 4. Each failure is evaluated on two factors for the matrix: how detrimental is the

effect to the mission of the facility and how probable is it that the failure will occur. In the matrix in Figure 4, the effects have been grouped into "catastrophic," "critical," "marginal," and "minor."

For most facilities, serious personnel injury or major equipment damage would be considered "catastrophic," and significant loss of production would be considered "critical." Reduced production may be considered "marginal," and a failure that did not affect production may be considered "minor."

The categories shown in the figure have been provided as an example. The gradient for an actual facility would have to be determined by the leadership for that facility. Depending on the facility, it could include such secondary effects as "failure to meet a delivery schedule" with an end effect of "loss of contract."

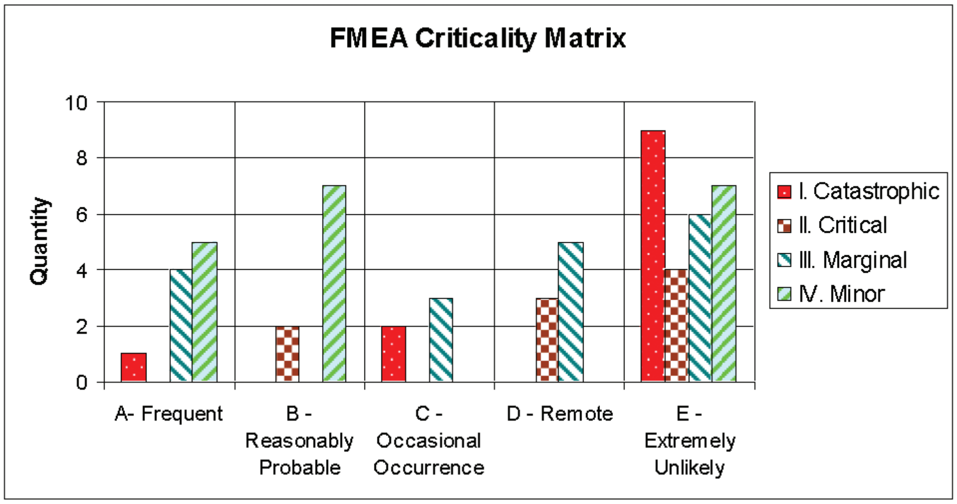

Figure 4—FMEA criticality matrix

The FMEA was performed to make the next step possible, which is the heart of the RCM analysis. The maintenance is now prioritized based on how detrimental the failure effect is and how likely it is to occur. If the effect is detrimental, but extremely unlikely, maintenance is not done. Maintenance is first performed where it will prevent failures that are both very likely *and* significantly detrimental. The process continues down the list of potential failures to the point of diminishing returns (failures that are least likely and have the smallest consequences).

7.5.2 Hidden/latent failures

As seen in the tables in the example above, some failures are "obvious" when they occur, such as the circuit breaker or fused switch that fails to close, with an end result of no power. These obvious failures are called *patent failures*. It should also be noted, however, that some failures are "hidden" failures. For example, the circuit breaker trip unit, which senses an overload or short-circuit condition, could be defective, and the only time the hidden failure is detected is when there is a fault on the circuit and the circuit breaker fails to operate. These hidden failures are called *latent failures*.

Therefore, the issue of latent failures should also be addressed as part of the RCM process. Some items, such as protective devices, require periodic testing to verify that they are operating properly. The trip unit and the current sensors for a circuit breaker are good examples of this type of device. The only way to find a defective trip unit is to test it. This situation is where the FMEA criticality matrix really becomes a valuable maintenance planning tool. "What does the circuit breaker supply power to?" becomes the driving force on how much maintenance it should receive. If the circuit breaker powers a lighting panel that is not critical to safety or production, it may not matter if it failed to trip, provided the upstream circuit breaker cleared the fault and its

operation would also not be critical to facility operations. Therefore, no preventive maintenance or testing would be performed (*run-to-failure*). However, if the circuit breaker provided power to the main production line, it would be important to maintain it.

Thorough acceptance testing of the equipment on initial installation can also be a significant factor in detecting some types of latent failures. If the facility had thorough acceptance testing performed, it is extremely likely that some latent failures, such as mis-installed equipment would have been found during the acceptance testing phase. A common example of this situation is reversed polarity on the neutral current sensor for the ground fault on the 480 V main circuit breaker. If the ground fault system were properly tested, this problem would be found and corrected before the facility was placed into service.

The probability of reversed polarity during installation is greater than the probability of the current sensor being defective or having the wrong ratio. Once the ground fault system has been tested, the polarity and the current sensor ratio have been verified; therefore, only the failure of a circuit breaker trip unit or current sensors while in service remains as potential latent failures.

The probability of a failure of the current sensors is less than that of the mechanism's failing to operate. Therefore, the mechanism should receive more attention than the current sensors. The probability of a failure of the trip unit is between the probability of a failure of the mechanism to operate (highest) and the current sensors (lowest). Therefore, the proper maintenance for the circuit breaker may be to perform cleaning and lubrication on the mechanism and secondary injection testing of the trip unit (using a special test set made by the manufacturer to test just the trip unit).

If acceptance testing was not performed, then the first time maintenance is performed, it would be advantageous to perform a primary injection test on the low-voltage circuit breakers and ground fault system (using a high-current test set that provides overload and short-circuit levels of current at low voltage) to make sure all the current sensors have the proper ratio and polarity. Primary injection testing provides a complete functional test of the circuit breaker at a low power level that does not damage the circuit breaker. An optimum maintenance program for circuit breakers in a manufacturing line is often to alternate between primary and secondary injection testing of the circuit breakers, such as performing primary injection every third or fifth time maintenance is performed (if the environment is clean and free of chemicals).

The definition of latent failure also includes equipment that was overstressed, but did not fail immediately. An excellent example of this occurs with surge protective devices (SPD). The metal-oxide varistors (MOV) often used in SPDs degrade with each operation. Eventually the MOV will no longer even withstand operating voltage and fails completely. Many SPD manufacturers provide overcurrent protection and monitoring of the internal status, often with indicating lights. When the SPD is so equipped, the failure is still "hidden" until someone goes around and inspects the installation and sees the indicating light.

7.5.3 Maintenance data

Generic maintenance data is a valuable tool when historical information is not available or when the engineering is establishing a maintenance-based line for a new system. This type of data is extremely rare but important to the establishment of a good RCM program. The following information is presented to the analyst to assist in the development of maintenance approaches including RCM. The data is an excerpt of the data collection effort defined and presented in IEEE Std 493-2007. Definitions and maintenance formulas can be found in that recommended practice. Maintenance data on the remaining components can be found in [B10].

8. Maintenance programs and tools

It is important to establish a maintenance program designed to manage the assets in your facility. There are several off the shelf tools that can be utilized to provide a comprehensive asset management tool. Computer maintenance management systems (CMMS) or computer maintenance management information systems (CMMIS) are software tools designed to manage the maintenance of an organizations assets. The stored

information is designed to track and organize maintenance in a proactive way to maximize the maintenance effectiveness. The tool can effectively manage the life cycle of the asset and provide useful decision making assessments for maintenance optimization specifically for your organization needs.

There are many tools available for both web based solutions hosted by the company selling the product or LAN based, meaning it is hosted but the user organization on their own server, as an internet search will quickly show. CMMS, utilized properly, can identify repair as well as replacement needed or previously performed for each asset tracked in the system. In addition, the tool can be used for consumables to assist in inventory planning and replacement periods.

Prior to establishing a maintenance management program, a comprehensive understanding of your assets is necessary to create a base line of information. This will provide the user with a basic understanding of the condition of the assets as well as the identification of each individual model and serial number or unique identifier of the asset. Below is a list of capabilities suggested to build a comprehensive maintenance management system:

— Operating locations to include a floor plan layout as well as a site layout of asset locations.
— Information support to include documentation such as drawings, procedures, tool list, skill levels, etc.
— Resources for tracking labor estimated and actual and the specific discipline necessary to complete the assigned activity.
— Safety plans for the documentation of policy and procedures as well as recording any incidents.
— Inventory control to include tracking of items being consumed and predicted stores for proactive maintenance procedures.
— Work request to allow personnel to enter issues related to the facility.
— Work order tracking to manage the daily, weekly, and monthly maintenance requirements to identify the needs of the assets for proper operation.
— Preventive maintenance programs to properly record and track maintenance requirements, procedures, time, and skill level required.
— Financial costs tied to inventory requirements and control.
— Contractual documents such as outsourced maintenance plans based on either asset needs or time-based maintenance.
— Key performance indicators design specifically for the organizations metrics for tracking performance.
— Flexibility to introduce specialized features such as reliability tracking, assessment, and performance important for RCM capabilities and future prediction of maintenance requirements.
— Labeling of assets with a unique identification tag such as a barcode system.

Each organization must determine the level of maintenance requirements and asset control important to the optimized operation of their facility. There is a wealth of information to consider and this section only highlights the basic information. The IEEE 3006 DOT standard series can assist in the comprehensive management of an organizations asset management providing the basic knowledge of proactive Reliability based Maintenance.

Annex A

(informative)

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